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***Abstract*- The authors investigate the effect of intermixing in InGaAs/GaAs quantum well structure using Cu-doped SiO_2. The incorporation of Cu into the silica film yields larger bandgap shift than typical impurity-free vacancy diffusion (IFVD) method at a lower activation temperature. We also observe enhancement of the photoluminescence (PL) signal from the intermixed InGaAs/GaAs quantum well structure after being cycle-annealed at 850 ºC.**

I. INTRODUCTION

Quantum well intermixing (QWI) methods has been successfully implemented to engineer the optical and material properties of semiconductor quantum heterostructures over the past decades [1]. The technique enables various benefits such as excellent alignment, negligible reflection losses, and intrinsic mode matching between integrated devices, hence providing a very enticing vision for the future of high-density photonic integrated circuits (PICs). Intermixing can be achieved using several techniques such as impurity free vacancy disordering (IFVD) [2], impurity induced disordering (IID) [3], laser-induced disordering [4], and plasma irradiation induced intermixing [5]. The intermixing process usually involves the introduction of defects especially vacancies and interstitials to the quantum well (QW) material. During high temperature annealing, the impurities or created point defects enhance the atomic interdiffusion rate between the quantum nanostructure and the barriers, and promote intermixing. As a result, the technique spatially modifies the material bandgap profile.

Among these well-established intermixing methods, IID is the only process which requires the introduction of impurities to create point defects in the QW structure. Although IID-based processes have been demonstrated to induce large degrees of QWI in both InP and GaAs structures, the optical quality of the disordered material is generally lower than that of the starting QWs. Typically, the IID process induces complex defects and loops that act as nonradiative recombination centers and photon scattering sources, hence, resulting in a shorter carrier lifetime and lower optical gain. This shortcoming imposes a limitation on the fabrication of high performance PICs using IID based processes.

In this paper, we investigate a highly reliable QWI process incorporating both IFVD and IID effects to induce QWI in a GaAs-based QW structure. The process is achieved by incorporating Cu into the silica cap via e-beam evaporation process. Cu has been known as a deep level impurity that has high diffusivity in semiconductor and dielectric materials including SiO_2 [6]. Using this technique, the intermixing rate of the QW structure is enhanced by the combination effects of group-III vacancy induced by the SiO_2 cap and Cu diffusion. High concentration of Cu in the semiconductor has been found to degrade the quality of the QW structure, as evident from the weak and noisy photoluminescence (PL) signal. In this work, an extended cycle annealing technique has been introduced to out-anneal Cu from the active epitaxy layer, and to restore the optical quality of the structure.

II. EXPERIMENTS

The InGaAs/GaAs double quantum well (DQW) structure grown by metal-organic vapor phase epitaxy (MOVPE) technique was used in this experiment. The DQW region was undoped and consisted of two 12 nm wide InGaAs QWs, separated by a 10 nm thick GaAs barrier and surrounded by 40 nm of GaAs. The structure was completed by 70 nm of additional separate confinement heterostructure (SCH) layers on each side and a 2000 nm thick lower cladding. The top capping layer consists of 300 nm thick undoped $In_{0.49}Ga_{0.51}P$. The as-grown material exhibits two photoluminescence peaks at 825 nm from the GaAs barrier layers and 900 nm from the InGaAs QW at 77 K.

Samples were first deposited with a 50 nm thick SiO_2 layer using plasma enhanced chemical vapor deposition (PECVD), followed by e-beam evaporation of a thin layer of ~ 1 nm Cu film. Subsequently, a 200 nm of SiO_2 was deposited to encapsulate the SiO_2/Cu structure. The purpose of the first SiO_2 layer is to modulate the concentration of Cu diffusion into the semiconductor. The intermixing stage was carried out by a rapid thermal processor (RTP). Samples were annealed under various temperatures for 2 minutes.

The samples were placed face down, sandwiched between two fresh pieces of GaAs proximity caps to provide an As overpressure environment during annealing process and to minimize the depletion of group-V elements from the semiconductor surface. For comparison, samples deposited with only 200 nm of SiO_2 were also included in the same annealing runs. The samples were characterized using PL spectroscopy after intermixing. The PL measurement was performed at 77 K using a 62.5-μm-diameter optical fiber as a signal probe and a 532 nm diode pumped solid state laser as an excitation source.

III. RESULTS AND DISCUSSIONS

Fig. 1 shows the 77 K PL spectra from the annealed Cu:SiO_2 InGaAs/GaAs DQW samples at temperature from 800 ºC to 900 ºC. Control samples with 200 nm thick SiO_2 (no Cu incorporation) were annealed to provide as a reference. The degree of intermixing progressively increases with increasing annealing temperature. A bandgap shift of 38 nm (61 meV) was observed from the Cu:SiO_2 intermixed sample annealed at 900 ºC while no significant shift (<10 nm) was observed from the control sample (shown as inset in Fig. 1(b)). Considering the small band offset between the barrier and the quantum well of 125 meV, the 61 meV blue shift represents almost 50 % of group-III elemental interdiffusion, which is considerably large.

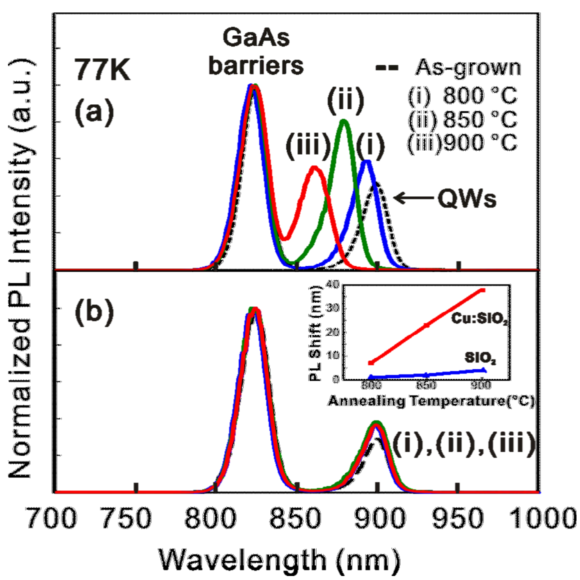

Fig. 1. PL spectra at 77 K from the InGaAs/GaAs DQW samples after annealed at various temperatures from 800 ºC to 900 ºC for (a) Cu:SiO_2 intermixed (b) Control samples. The spectrum of the as-grown sample is represented by the dotted line. For clarity, all PL signals are normalized with the barrier signal of the as-grown sample.

Compared to the IFVD process using only the SiO_2 cap, a lower activation energy and larger degree of QWI have been measured from samples intermixed using the Cu:SiO_2 process. Generally, a higher activation is required for the generation of group-III vacancy [7]. Comparing the conventional SiO_2-IFVD and Cu:SiO_2 induced QWI, we conclude that the large bandgap shift observed from the Cu:SiO_2 QWI is dominated by the Cu-diffusion induced disordering.

The postulation of Cu-diffusion induced QWI is further evident by the observation of significant PL degradation from sample annealed at 850 ºC for 2 minutes (Fig. 2). The presence of Cu in the active QW has been correlated to the degradation of the PL signal [6]. In our case, the QWs are placed ~ 480 nm below the surface. Cu diffused from the SiO_2 layer into the QWs region might have attributed to the significant degradation of the PL signal. To overcome this issue, we employed a cycle-annealing approach aiming at out-annealing the Cu-related centers from the epilayer region and fully restoring the crystal quality of the material.

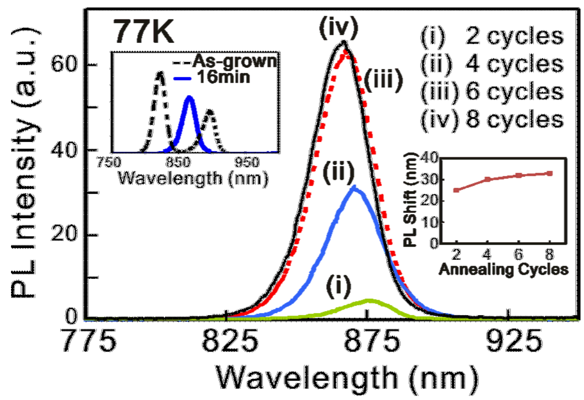

Fig. 2. 77 K PL spectra from the Cu:SiO_2 intermxed InGaAs/GaAs DQW sample after annealed at 800 ºC for [(i) 2 , (ii) 4 , (iii) 6, (iv) 8 cycles].

The cycle-annealing process is achieved by subsequent annealing the intermixed samples (i.e., sample capped with Cu-SiO_2 and annealed at 850 ºC for 2 min) with cycles of RTP at 50 ºC below the intermixing temperature (i.e., 800 ºC for 2 minutes). The cycle of annealing performed at below the intermixing activation energy allows recrystalizing and out-annealing of residual Cu in the material without significantly extending the bandgap shift.

The sample intermixed at 850 ºC for 2 minutes exhibits a PL integral power of 40 dB lower than the as-grown sample. With subsequent annealing at 800 ºC for 2minutes, the PL strength increases by 13 dB. Fig. 2 shows the evolution of the PL intensity for sample subjected to 2-8 annealing cycles. The signal of the PL makes a fully recovery after sample is annealed at 800 ºC for 8 cycles.

The right inset in Fig. 2 summarizes the wavelength blueshift versus the number of annealing cycles, while the left inset compares the PL signal from the as-grown sample. Compared to the 850 ºC intermixed sample, narrower PL linewidths were observed from the subsequent annealed sample suggesting an improvement of material quality (Fig. 3).

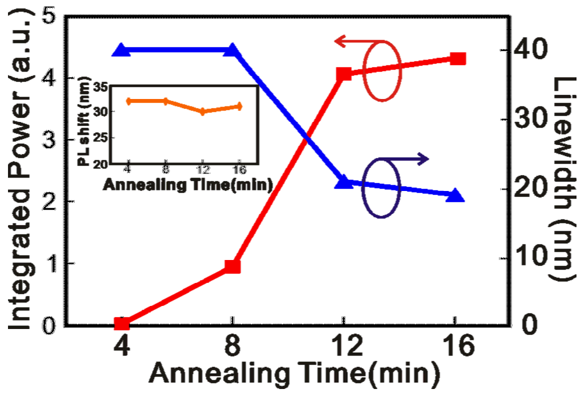

Fig.3. Integrated Power and Linewidth vs. annealing time. from the InGaAs/GaAs DQW samples annealed at 800 ºC

IV. CONCLUSION

In summary, we have demonstrated a highly selective and reproducible Cu-doped SiO_2 intermixing in InGaAs/GaAs QWs heterostructure. A differential blueshift as large as 38 nm (61 meV) has been observed from the Cu:SiO_2 intermixed sample. Extended cycle annealing technique has been introduced to out-anneal Cu impurity from the active epitaxy layer, and to restore the optical quality of the structure. The signal of the PL makes a fully recovery after annealing at 800 ºC for 8 cycles.

V. ACKNOWLEDGMENTS

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